

TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371		ATTORNEY'S DOCKET NUMBER  162/540
		U.S. APPLICATION NO. (If known, see 37 CFR 1.5)  <b>09/446525</b>
INTERNATIONAL APPLICATION NO.  PCT/JP98/02915	INTERNATIONAL FILING DATE  June 30, 1998	PRIORITY DATE CLAIMED  June 30, 1997
TITLE OF INVENTION  <b>CRYPTOGRAPHIC DEVICE</b>		
APPLICANT(S) FOR DO/EO/US  1) Masayuki KANDA, 2) Youichi TAKASHIMA, 3) Katsuhiki AOKI and 4) Tsutomu MATSUMOTO		
Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:		
<p>1. <input checked="" type="checkbox"/> This is a <b>FIRST</b> submission of items concerning a filing under 35 U.S.C. 371</p> <p>2. <input type="checkbox"/> This is a <b>SECOND</b> or <b>SUBSEQUENT</b> submission of items concerning a filing under 35 U.S.C. § 371.</p> <p>3. <input type="checkbox"/> This express request to begin national examination procedures (35 U.S.C. 371(f)) at any time rather than delay examination until the expiration of the applicable time limit set in 35 U.S.C. 371(b) and PCT Articles 22 and 39(1).</p> <p>4. <input type="checkbox"/> A proper Demand for International Preliminary Examination was made by the 19th month from the earliest claimed priority date.</p> <p>5. <input checked="" type="checkbox"/> A copy of the International Application as filed (35 U.S.C. 371(c)(2))        a. <input checked="" type="checkbox"/> is transmitted herewith (required only if not transmitted by the International Bureau).        b. <input checked="" type="checkbox"/> has been transmitted by the International Bureau.        c. <input type="checkbox"/> is not required, as the application was filed in the United States Receiving Office (RO/US).</p> <p>6. <input type="checkbox"/> A translation of the International Application into English (35 U.S.C. 371(c)(2)).</p> <p>7. <input type="checkbox"/> Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371(c)(3))        a. <input type="checkbox"/> are transmitted herewith (required only if not transmitted by the International Bureau).        b. <input type="checkbox"/> have been transmitted by the International Bureau.        c. <input type="checkbox"/> have not been made; however, the time limit for making such amendments has NOT expired.        d. <input type="checkbox"/> have not been made and will not be made.</p> <p>8. <input type="checkbox"/> A translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).</p> <p>9. <input checked="" type="checkbox"/> An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4)).</p> <p>10. <input type="checkbox"/> A translation of the Annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371(c)(5)).</p>		
Items 11. to 16. below concern other document(s) or information included:		
<p>11. <input checked="" type="checkbox"/> An Information Disclosure Statement under 37 CFR 1.97 and 1.98 (and 5 references).</p> <p>12. <input checked="" type="checkbox"/> An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.</p> <p>13. <input type="checkbox"/> A <b>FIRST</b> preliminary amendment.  <input type="checkbox"/> A <b>SECOND</b> or <b>SUBSEQUENT</b> preliminary amendment.</p> <p>14. <input type="checkbox"/> A substitute specification.</p> <p>15. <input type="checkbox"/> A change of power of attorney and/or address letter</p> <p>16. <input checked="" type="checkbox"/> Other items or information:        Verified translation of application as filed; nine (9) sheets formal drawings</p>		

U.S. APPLICATION NO. (If known, see 37 CFR 1.5) <b>09/446525</b>	INTERNATIONAL APPLICATION NO. PCT/JP98/02915	ATTORNEY'S DOCKET NUMBER 162/540	
The following fees are submitted:		CALCULATIONS      PTO USE ONLY	
<input checked="" type="checkbox"/> Basic National Fee (37 CFR 1.492(a)(1)-(5)): Search Report has been prepared by the EPO or JPO      \$840.00 International preliminary examination fee paid to USPTO (37 CFR 1.482)  \$670.00 No international preliminary examination fee paid to USPTO (37 CFR 1.482) but international search fee paid to USPTO (37 CFR 1.445(a)(2))      \$760.00  Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO      \$970.00  International preliminary examination fee paid to USPTO (37 CFR 1.482) and all claims satisfied provisions of PCT Article 33(2)-(4) <b>\$96.00</b>			
<b>ENTER APPROPRIATE BASIC FEE AMOUNT</b> = <b>\$840.00</b>			
Surcharge of <b>\$130.00</b> for furnishing the oath or declaration later than <input type="checkbox"/> 20 <input type="checkbox"/> 30 months from the earliest claimed priority date (37 CFR 1.492(e)).		<b>\$0.00</b>	
Claims	Number Filed	Number Extra	Rate
Total Claims	232-20 =	212	X <b>\$18.00</b>
Independent Claims	1- 3 =	0	X <b>\$78.00</b>
Multiple dependent claim(s)(if applicable)		+ <b>\$260.00</b>	<b>\$260.00</b>
<b>TOTAL OF ABOVE CALCULATIONS</b> =		<b>\$4,076.00</b>	
Reduction by 1/2 for filing by small entity, if applicable. Verified Small Entity statement must also be filed. (Note 37 CFR 1.9, 1.27, 1.28)		\$	
<b>SUBTOTAL</b> =		<b>\$4,076.00</b>	
Processing fee of <b>\$130.00</b> for furnishing the English translation later than <input type="checkbox"/> 20 <input type="checkbox"/> 30 months from the earliest claimed priority date (37 CFR 1.492(e)).		\$	
<b>TOTAL NATIONAL FEE</b> =		<b>\$4,076.00</b>	
Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31). <b>\$40.00</b> per property +		<b>\$40.00</b>	
<b>TOTAL FEES ENCLOSED</b> =		<b>\$4,116.00</b>	
		Amount to be: refunded      \$ charged      \$	
a. A check in the amount of \$4,116 to cover the above fees is enclosed.			
b. <input type="checkbox"/> Please charge my Deposit Account No. <b>22-0185</b> in the amount of \$ _____ to cover the above fees. A duplicate copy of this sheet is enclosed.			
c. The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. <b>22-0185</b> . A duplicate copy of this sheet is enclosed.			
NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b) must be filed and granted to restore the application to pending status			
SEND ALL CORRESPONDENCE TO:			
 <b>George R. Pettit</b> <b>27,369</b> SIGNATURE			
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<b>George R. Pettit</b> <b>27,369</b> REGISTRATION NUMBER			
December 27, 1999			

09/446525

416 Rec'd PCT/PTO 27 DEC 1999  
IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of:

Masayuki KANDA, et al.

Appln. No. To be assigned  
(U.S. Ntl. Phase of PCT/JP98/02915) :

Art Unit: Unassigned

Filed: December 27, 1999

Examiner: Unassigned

For: CRYPTOGRAPHIC DEVICE

Atty Docket: 162/540

**PRELIMINARY AMENDMENT**

Assistant Commissioner for Patents  
Washington, D.C. 20231

Sir:

Prior to examination on the merits, please amend the above-identified patent application as follows:

**IN THE SPECIFICATION:**

Please amend the specification as follows:

Page 6,

line 10, change "difference mask" to --output mask--.

Page 15,

line 9, change "part 34" to --part 347--.

**IN THE CLAIMS:**

Kindly cancel existing claims 1-13 and add the following new claims:

--14. A cryptographic device which encrypts input data by sequentially processing it by a plurality of round processing which nonlinearly transforms it using extended key, comprising:  
an initial splitting part which splits said input data to two pieces of block data;  
a key storage part for storing extended key;  
a plurality of cascade-connected round processing parts which are supplied with said two pieces of block data and sequentially process them using said extended key; and  
a final combining part which combines two pieces of block data output from the last round of said plurality of cascade-connected round processing parts into a single piece of data and outputs it;

wherein each of said plurality of round processing part comprises:

a non-linear function part which transforms one of two pieces of block data input thereto from the preceding stage, depending on extended key stored in said key storage part;

a linear operation part which linearly operates the output data from said nonlinear function part and the other of said two pieces of block data; and

a swapping part which swaps the output data from said linear operation part and the input block data to said nonlinear function part and provides the two pieces of swapped data as two pieces of input block data to said round processing part of the next round; and

wherein said nonlinear function part comprises:

a key-dependent linear transformation part which linearly transforms input data based on extended key stored in said key storage part to thereby generate transformed data;

a splitting part which splits the transformed data from said key-dependent linear transformation part to a plurality of bit strings;

a plurality of first nonlinear transformation parts which nonlinearly transform said plurality of bit strings, respectively, and output transformed data;

a first linear transformation part which linearly transforms said transformed data from said plurality of first nonlinear transformation parts in association with each other and outputs a plurality of pieces of uniformed data to a plurality of routes, respectively;

a second nonlinear transformation part provided in at least one of said plurality of routes, for nonlinearly transforming said transformation parts, and for outputting the transformed data as data of that route; and

a combining part which combines data from said plurality of routes into output data of said nonlinear function part.

15. The cryptographic device of claim 14, wherein said first linear transformation part comprises a key-dependent linear operation part which linearly transforms said plurality of pieces of uniformed data based on extended key stored in said key storage part and outputs the plurality of transformed data as data of said plurality of routes.

16. The cryptographic device of claim 15, further comprising a second linear transformation part which linearly transforms the output data from said combining part to provide the output data of said nonlinear function part.

17. The cryptographic device of claim 16, wherein said second linear transformation part is a linear transformation part which performs a linear transformation base don extended key stored in said key storage part.

18. The cryptographic device of claim 17, wherein said first linear transformation part comprises at least one exclusive OR circuit provided in each of said plurality of routes, for outputting said uniformed data to said each route by an exclusive-OR operation of data of said each route and data of other routes.

19. The cryptographic device of claim 14, further comprising a

second linear transformation part which linearly transforms the output data of said combining part to provide the transformed data as output data of said nonlinear function part.

20. The cryptographic device of claim 19, wherein said second linear transformation part is a linear transformation part which performs a linear transformation based on extended key stored in said key storage part.

USPTO Searcher

21. The cryptographic device of claim 19, wherein said first linear transformation part comprises at least one exclusive OR circuit provided in each of said plurality of routes, for outputting said uniformed data to said each route by an exclusive-OR operation of data of said each route and data of other routes.

22. The cryptographic device of any one of claims 14 through 21, further comprising an initial linear transformation part which linearly transforms said input data and supplies it to said initial splitting part.

23. The cryptographic device of claim 22, wherein said initial linear transformation part is a transformation part which performs a linear transformation based on extended key stored in said key storage part.
24. The cryptographic device of claim 23, further comprising a final linear transformation part which linearly transforms the output data of said final combining part to provide it as the output of said cryptographic device.
25. The cryptographic device of claim 24, wherein said final linear transformation part is a transformation part which performs a linear transformation based on extended key stored in said key storage part.
26. The cryptographic device of claim 22, further comprising a final linear transformation part which linearly transforms the output data of said final combining part to provide it as the output of said cryptographic device.
27. The cryptographic device of claim 26, wherein said final linear

transformation part is a transformation part which performs a linear transformation based on extended key stored in said key storage part.

28. The cryptographic device of claim 26, wherein said plurality of routes are first, second, third and fourth routes arranged in this order.

29. The cryptographic device of claim 28, wherein said second nonlinear transformation part is provided in each of said four routes.

30. The cryptographic device of claim 28, wherein said second nonlinear transformation part is provided in each of said first and fourth routes.

31. The cryptographic device of claim 30, wherein said first linear transformation part comprises:

a first exclusive OR circuit provided in said second route, for carrying out the exclusive-OR between data of said first route and data of said second route;

a second exclusive-OR circuit provided in said third route, for carrying out the exclusive OR between data of said fourth route and data of said third route;

a third exclusive-OR circuit provided in said third route, for carrying out the exclusive OR between the output of said second exclusive-OR circuit and the output of said first exclusive-OR circuit;

a fourth exclusive-OR circuit provided in said second route, for carrying out the exclusive OR between the output of said first exclusive-OR circuit and the output of said third exclusive-OR circuit;

a fifth exclusive-OR circuit provided in said first route, for carrying out the exclusive OR between the output of said first exclusive-OR circuit and the output of said fourth exclusive-OR circuit;

a sixth exclusive-OR circuit provided in said fourth route, for carrying out the exclusive OR between the data of said fourth route and the output of said third exclusive-OR circuit.

32. The cryptographic device of claim 23, wherein said plurality of routes are first, second, third and fourth routes arranged in this order.

33. The cryptographic device of claim 32, wherein said second nonlinear transformation part is provided in each of said four routes.

34. The cryptographic device of claim 32, wherein said second nonlinear transformation part is provided in each of said first and fourth routes.

35. The cryptographic device of claim 34, wherein said first linear transformation part comprises:

a first exclusive OR circuit provided in said second route, for carrying out the exclusive-OR between data of said first route and data of said second route;

a second exclusive-OR circuit provided in said third route, for carrying out the exclusive OR between data of said fourth route and data of said third route;

a third exclusive-OR circuit provided in said third route, for carrying out the exclusive OR between the output of said second exclusive-OR circuit and the output of said first exclusive-OR circuit;

a fourth exclusive-OR circuit provided in said second route, for carrying out the exclusive OR between the output of said first exclusive-OR circuit and the output of said third exclusive-OR circuit;

a fifth exclusive-OR circuit provided in said first route, for carrying out the exclusive OR between the data of said first route and the output of said fourth exclusive-OR circuit; and

a sixth exclusive-OR circuit provided in said fourth route, for carrying out the exclusive OR between the data of said fourth route and the output of said third exclusive-OR circuit.

36. The cryptographic device of claims 25, wherein said plurality of routes are first, second, third and fourth routes arranged in this order.

37. The cryptographic device of claim 33, wherein said second nonlinear transformation part is provided in each of said four routes.

38. The cryptographic device of claim 33, wherein said second nonlinear transformation part is provided in each of said first and fourth

routes.

39. The cryptographic device of claim 35, wherein said first linear transformation part comprises;

a first exclusive OR circuit provided in said second route, for carrying out the exclusive-OR between data of said first route and data of said second route;

a second exclusive-OR circuit provided in said third route, for carrying out the exclusive OR between data of said fourth route and data of said third route;

a third exclusive-OR circuit provided in said third route, for carrying out the exclusive OR between the output of said second exclusive-OR circuit and the output of said first exclusive-OR circuit;

a fourth exclusive-OR circuit provided in said second route, for carrying out the exclusive OR between the output of said first exclusive-OR circuit and the output of said third exclusive-OR circuit;

a fifth exclusive-OR circuit provided in said first route, for carrying out the exclusive OR between the data of said first route and the

output of said fourth exclusive-OR circuit; and

a sixth exclusive-OR circuit provided in said fourth route, for carrying out the exclusive OR between the data of said fourth route and the output of said third exclusive-OR circuit.

40. The cryptographic device of any one of claims 14 through 21, further comprising a final linear transformation part which linearly transforms the output data of said final combining part to provide it as the output of said cryptographic device.

41. The cryptographic device of claim 40, wherein said final linear transformation part is a transformation part which performs a linear transformation based on extended key stored in said key storage part.

42. The cryptographic device of claim 40, wherein said plurality of routes are first, second, third and fourth routes arranged in this order.

43. The cryptographic device of claim 42, wherein said second

nonlinear transformation part is provided in each of said four routes.

44. The cryptographic device of claim 42, wherein said second nonlinear transformation part is provided in each of said first and fourth routes.

45. The cryptographic device of claim 44, wherein said first linear transformation part comprises:

a first exclusive OR circuit provided in said second route, for carrying out the exclusive-OR between data of said first route and data of said second route;

a second exclusive-OR circuit provided in said third route, for carrying out the exclusive OR between data of said fourth route and data of said third route;

a third exclusive-OR circuit provided in said third route, for carrying out the exclusive OR between the output of said second exclusive-OR circuit and the output of said first exclusive-OR circuit;

a fourth exclusive-OR circuit provided in said second route, for

carrying out the exclusive OR between the output of said first exclusive-OR circuit and the output of said third exclusive-OR circuit;

a fifth exclusive-OR circuit provided in said first route, for carrying out the exclusive OR between the data of said first route and the output of said fourth exclusive-OR circuit; and

a sixth exclusive-OR circuit provided in said fourth route, for carrying out the exclusive OR between the data of said fourth route and the output of said third exclusive-OR circuit.

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46. The cryptographic device of any one of claims 14 through 21, wherein said plurality of routes are first, second, third and fourth routes arranged in this order.

47. The cryptographic device of claim 46, wherein said second nonlinear transformation part is provided in each of said four routes.

48. The cryptographic device of claim 46, wherein said second nonlinear transformation part is provided in each of said first and fourth

routes.

49. The cryptographic device of claim 48, wherein said first linear transformation part comprises:

a first exclusive Or circuit provided in said second route, for carrying out the exclusive OR between data of said fourth route and data of said third route;

a third exclusive-OR circuit provided in said third route, for carrying out the exclusive OR between the output of said second exclusive-OR circuit and the output of said first exclusive-OR circuit;

a fourth circuit-OR circuit provided in said second route, for carrying out the exclusive OR between the output of said first exclusive-OR circuit and the output of said third exclusive-OR circuit;

a fifth exclusive-OR circuit provided in said first route, for carrying out the exclusive OR between the data of said first route and the output of said fourth exclusive-OR circuit; and

a sixth exclusive-OR circuit provided in said fourth route, for carrying out the exclusive OR between the data of said fourth route and the

output of said third exclusive-OR circuit.--

**REMARKS**

Claims 14-49 are pending in the application.

The specification has been amended to correct minor typographic errors noted when the specification was translated into English, and the claims have been revised to more clearly describe the invention. No new matter has been added.

Examination on the merits of the above patent application is respectfully requested.

Respectfully submitted,



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## CRYPTOGRAPHIC DEVICE

### TECHNICAL FIELD

The present invention relates to an encryption device for concealing data in data communication or storage and, more particularly, to an encryption device of a secret-key algorithm which encrypts or decrypts data in blocks using a secret key.

A typical secret-key algorithm, which is used in an encryption device to conceal data, is the DES (Data Encryption Standard) that is a FIPS-approved algorithm for encryption (FIPS 46-3).

Fig. 1 illustrates the functional configuration of the DES. The DES uses a 56-bit secret key to encrypt or decrypt data in blocks of 64 bits. In Fig. 1 the encryption process begins with the initial permutation of 64 bits of a plaintext  $P$  in an initial perminutation part 11 which is followed by splitting the transformed data into two pieces of 32-bit block data  $L_0$  and  $R_0$ . The block data  $R_0$  is input into a function operation part (which is commonly called a round function) 12 shown as an  $i$ -th round processing part  $14_i$  ( $i=0, 1, \dots, 15$ ) in Fig. 2, wherein it is transformed to  $f(R_0, k_0)$  using a 48-bit extended key  $k_0$ . This transformed data  $(R_0, k_0)$  and the block data  $L_0$  are exclusive ORed in an XOR circuit 13, and its output and the block data  $R_0$  are interchanged to obtain the next block data  $L_1, R_1$ . That is,

$$\begin{aligned} R_1 &= L_0 \oplus f(R_0, k_0) \\ L_1 &= R_0 \end{aligned} \tag{1}$$

A 0-th round processing part  $14_0$  is comprises an operation part 12, an exclusive OR circuit 13 and a data swapping part, by

which two pieces of input data  $L_0$  and  $R_0$  are subjected to round processing to provide output block data  $L_1$  and  $R_1$ , and similar round processing parts  $14_1$  to  $14_{15}$  are provided in cascade. The processing by the  $i$ -th round processing part  $14_i$  will hereinafter be referred to  
5 as  $i$ -th processing, where  $i=0, \dots, 15$ . That is, each round processing part  $14_i$  ( $0 \leq i < 15$ ) performs the following processing

$$\begin{aligned} R_{i+1} &= L_i \oplus f(R_i, k_i) \\ L_{i+1} &= R_i \end{aligned} \tag{2}$$

and finally combines two pieces of data  $R_{16}$  and  $L_{16}$  into 64-bit data,  
10 which is transformed in a final permutation part 15 to provide a 64-bit ciphertext. The decryption processing can be performed following the same procedure as that for the encryption processing except inputting extended keys  $k_0, k_1, \dots, k_{14}, k_{15}$  into a function  $f$  in the order  $k_{15}, k_{14}, \dots, k_1, k_0$  which is reverse to that in the encryption  
15 processing. In such an instance, the outputs  $L_{16}$  and  $R_{16}$  from the final round processing part  $14_{15}$  are further swapped as depicted, and in the decryption processing the plaintext is provided intact at the output of the final permutation part 15 by inputting the ciphertext into the initial permutation part 11 to subject it to the  
20 processing of Fig. 1. Of course, exactly the same result could be obtained even by providing data to the final permutation part 15 without swapping the outputs of the final round processing part  $14_{15}$ . Incidentally, the extended keys  $k_0, k_1, \dots, k_{14}, k_{15}$  are generated by extending a 56-bit secret key to 16 48-bit extended  
25 keys with a total of 768 bits in an extended key generation part 16 separate of the encryption processing.

The processing in the function operation part 12 is performed as

shown in Fig. 2. To begin with, the 32-bit block data  $R_1$  is transformed to 48-bit data  $E(R_1)$  in an extended permutation part 17. This output data and the extended key  $k_1$  are exclusive ORed in an XOR circuit 18, whose output is transformed to 48-bit data 5  $E(R_1) \oplus k_1$ , which is then split to eight pieces of 6-bit sub-block data. The eight pieces of sub-block data are input into different S-boxes  $S_1$  to  $S_8$  to derive therefrom a 4-bit output, respectively. Incidentally, 10 the S-box  $S_j$  ( $j=1, \dots, 8$ ) is a nonlinear transformation table that transforms the 6-bit input data to the 4-bit output data, and this is a part that assumes a key role essentially in providing security for the DES. The eight pieces of output data from the S-boxes  $S_1$  to  $S_8$  are concatenated again to 32-bit data, which is applied to a transpose 15 part 19 to obtain an output  $f(R_1, k_1)$  of the function  $f$  which is exclusive ORed with  $L_1$  as depicted in Fig. 8.

Next, a description will be given of cryptanalysis techniques. A wide variety of cryptanalysis techniques have been proposed for the DES and other traditional secret-key algorithms; extremely effective cryptanalysis techniques among them are a differential 20 cryptanalysis technique proposed by E. Biham and A. Shamir ("Differential Cryptanalysis of DES-like Cryptosystems," Proceedings of CRYPTO'90) and a linear cryptanalysis technique proposed by Matsui (Linear Cryptanalysis (I) of DES Cryptosystem," The 1993 Symposium on Cryptography and Information Security 1993, SCIS93-3C).

With the difference between two pieces of data  $X$  and  $X^*$  defined as

$$\Delta X = X \oplus X^* \quad (3)$$

the differential cryptanalysis aims to obtain the extended key  $k_{15}$  in the final round by applying to the following equations two sets of plaintext-ciphertext pairs that an attacker possesses. Let  $L_i$  and  $R_i$  represent two pieces of block data for a first plaintext input into each round processing part  $14_i$  of Fig. 1 and  $L^*_i$  and  $R^*_i$  represent two pieces of block data for a second plaintext input into each round processing part  $14_i$ . And let it be assumed that ciphertexts are provided in response to the input of these first and second plaintexts. Under the definition of Eq. (3), it holds that

$$\begin{aligned} 10 \quad \Delta L_i &= L_i \oplus L_i^* \\ \Delta R_i &= R_i \oplus R_i^* \end{aligned} \quad (4)$$

In Fig. 1, since  $L_{15} = R_{14}$ ,  $L^*_{15} = R^*_{14}$ ,  $L_{16} = R_{15}$  and  $L^*_{16} = R^*_{15}$ , the following equations hold

$$R_{16} = L_{15} \oplus f(R_{15}, k_{15})$$

$$R^*_{16} = L^*_{15} \oplus f(R^*_{15}, k_{15}) \quad (5)$$

and the exclusive OR of both sides of these two equations is obtained as follows:

$$\Delta R_{16} = \Delta L_{15} \oplus f(L_{16}, k_{15}) \oplus f(L_{16} \oplus \Delta L_{16}, k_{15}) \quad (6)$$

The exclusive ORing of its both sides with  $\Delta R_{14} = \Delta L_{15}$  gives the following equation:

$$f(L_{16}, k_{15}) \oplus f((L_{16} \oplus \Delta L_{16}), k_{15}) = \Delta R_{16} \oplus \Delta R_{14} \quad (7)$$

At this time,  $L_{16}$ ,  $\Delta L_{16}$  and  $\Delta R_{16}$  are data available from the ciphertext, and hence they are known information. Hence, if the attacker can correctly obtain  $\Delta R_{14}$ , then only  $k_{15}$  in the above equation becomes an unknown constant; the attacker can find a correct  $k_{15}$  without fail by making an exhaustive search for  $k_{15}$  through utilization of the known sets of plaintext-ciphertext pairs.

On the other hand,  $\Delta R_{14}$  is difficult in general to obtain since this value is an intermediate difference value. Then, assume that the each round processing part  $14_i$  are approximated by the following equations with a probability  $p_i$  in each of the 0-th to the last round

5 but one:

$$\begin{aligned}\Delta R_{i+1} &= \Delta L_i \oplus \Delta\{f(\Delta R_i)\} \\ \Delta L_{i+1} &= \Delta R_{i+1}\end{aligned}\quad (8)$$

The point is that when certain  $\Delta R_i$  is input,  $\Delta\{f(\Delta R_i)\}$  can be predicted with the probability  $p_i$  regardless of the value of the extended key

10  $k_i$ . The reason for which such approximations can be made is that  $\Delta\{f(\Delta R_i)\}$  is affected only by the S-box part which is a nonlinear transformation table, and that according to the input differences thereto, the S-boxes provide an extremely uneven distribution of difference outputs. For example, in the S-box S1, an input difference

15 "110100" is transformed to an output difference "0010" with a probability of 1/4. Then, the approximation for each round is obtained by assuming that each S-box is capable of predicting the relationship between the input difference and the output difference with a probability of  $p_{si}$  and by combining them. Furthermore, the

20 concatenation of such approximations in the respective rounds makes it possible to obtain  $\Delta R_{14}$  from  $\Delta L_0$  and  $\Delta R_0$  ( $\Delta L_0$  and  $\Delta R_0$  are data derivable from the plaintext, and hence they are known.) with a probability of  $P = \prod p_i$ . Incidentally, the higher the probability  $P$ , the easier the cryptanalysis. After the extended key  $k_{15}$  is thus

25 obtained, a similar calculation is made of the extended key  $k_{14}$  regarding it as a 15-round DES that is one round fewer than in the above; such operations are repeated to obtain the extended keys one

by one to  $k_0$ .

Biham et al. say that the DES could be broken by this cryptanalysis if  $2^{47}$  sets of chosen plaintext-ciphertext pairs are available.

5       The linear cryptanalysis aims to obtain extended keys by constructing the following linear approximate expression and using the maximum likelihood method with sets of known plaintext-ciphertext pairs to the attacker.

10      
$$(L_0, R_0) \cdot \Gamma(L_0, R_0) \oplus (L_{16}, R_{16}) \cdot \Gamma(L_{16}, R_{16}) \\ = (k_0, k_1, \dots, k_{15}) \cdot \Gamma(k_0, k_1, \dots, k_{15}) \quad (9)$$

where  $\Gamma(X)$  represents the vector that chooses a particular bit position of  $X$ , and it is called a mask value.

15      The role of the linear approximate expression is to approximately replace the cryptographic algorithm with a linear expression and separate it into a part concerning the set of plaintext and ciphertext and a part concerning the extended key. That is, in the set of plaintext-ciphertext pair, the exclusive ORs between the values at particular bit positions of the plaintext and those of the ciphertext all take a fixed value, which indicates that it equals the 20 exclusive OR of the values at particular bit positions of extended keys. This means that the attacker gets information

$$(k_0, k_1, \dots, k_{15}) \cdot \Gamma(k_0, k_1, \dots, k_{15}) \quad (1 \text{ bit})$$

from information

$$(L_0, R_0) \cdot \Gamma(L_0, R_0) \oplus (L_{16}, R_{16}) \cdot \Gamma(L_{16}, R_{16}).$$

25      At this time,  $(L_0, R_0)$  and  $(L_{16}, R_{16})$  are the plaintext and the ciphertext, and hence they are known. For this reason, if the attacker can correctly obtain  $\Gamma(L_0, R_0)$ ,  $\Gamma(L_{16}, R_{16})$  and  $\Gamma(k_0, k_1, \dots,$

$k_{15}$  , then he can obtain  $(k_0, k_1, \dots, k_{15}) \cdot \Gamma(k_0, k_1, \dots, k_{15})$  (1 bit).

In the DES, it is only in the S-box that the nonlinear transformation is performed; hence, if only the S-box can be linearly represented, the linear approximate expression can easily be constructed. Then, assume that each S-box  $S_i$  can be linearly represented with a probability of  $p_{si}$ . The point here is that when the input mask value for the S-box is given, its output mask value can be predicted with the probability of  $p_{si}$ . The reason for this is that the S-boxes, which form a nonlinear transformation table, provide an extremely uneven distribution of difference mask values according to the input mask values. For example, in the S-box S5, when the input mask value is "010000," an output mask value "1111" is predicted with a probability of 3/16. By combining mask values in these S-boxes, a linear approximation can be made in each round between the input mask value and the output mask value with a probability  $p_i$ , and by concatenating the linear approximations in the respective rounds,  $\Gamma(L_0, R_0)$ ,  $\Gamma(L_{16}, R_{16})$  and  $\Gamma(k_0, k_1, \dots, K15)$  are obtained with the following probability:

$$P = 2^{n-1} \prod p_i - 1/2 \quad (10)$$

Here, the higher the probability P, the easier the cryptanalysis.

According to Matsui, he has succeeded in the analysis of the DES by this cryptanalysis through utilization of  $2^{43}$  sets of known plaintext-ciphertext pairs.

To compete against the above cryptanalysis techniques, the probability P needs only to be reduced to a sufficiently low. Accordingly, a wide variety of proposals have been made to lessen the probability P, and the easiest way to provide increased security

in the conventional cryptosystem is to increase the number of rounds. For example, a Triple-DES formed by a concatenation of three DESs essentially increases the number of rounds from 16 to 48, and it provides a far lower probability P than in the case of the DES.

5        However, to increase the number of rounds with a view to competing against the cryptanalysis techniques described above inevitably enlarges the scale of the cryptographic device used and increases the amount of data to process as well. For example, if the number of rounds is tripled, the workload for encryption will also  
10      increase threefold. That is, since the encryption speed of the present DES is about 10 Mbps in the Pentium PC class, the encryption speed of the Triple-DES goes down to around 3.5 Mbps. On the other hand, networks and computers are becoming increasingly faster year by year, and hence there is also a demand for encryption devices that  
15      keep up with such speedups. With conventional cryptographic devices, it is extremely difficult, therefore, to simultaneously meet the requirements of speedup and security.

20       The present invention is intended to obviate the abovesaid defects of the prior art and has for its object to provide a cryptographic device that satisfies the security requirement without increasing the number of rounds.

#### DISCLOSURE OF THE INVENTION

25       The present invention is characterized in that a nonlinear function part, in particular, is provided with: a key-dependent linear transformation part which linearly transforms input data of the nonlinear function part based on key data stored in a key storage

part; a splitting part which splits the output data of the key-dependent linear transformation part to a plurality of bits strings; first nonlinear transformation parts which nonlinearly transform these split bit strings, respectively; a first linear transformation part which 5 linearly transforms the respective output bits strings of the first nonlinear transformation parts in association with each other; second nonlinear transformation parts which nonlinearly transform some or all of the output bit strings of the first linear transformation part; and a combining part which combines the output bit strings of the 10 second nonlinear transformation parts into output data of the nonlinear function part.

To provide increased security, the invention is characterized by a second linear transformation part which linearly transforms the output data of the combining part to the output data of the nonlinear function part. 15

Furthermore, the invention is characterized in that either one or both of the first and second linear transformation parts are key-dependent linear transformation parts which linearly transform the input data thereto based on key data stored in the key storage part.

According to the present invention, it is guaranteed that when 20 the probability in the S-boxes is  $p_{si} \leq p_b < 1$  (where  $p_b$  is the maximum differential or linear probability in the S-boxes), the probability of approximating each round is  $p_i \leq p_b^2$  (when the input difference to the function  $f$  is not 0 in the case of the differential cryptanalysis, and when the output mask value from the function  $f$  is not 0 in the case of the linear cryptanalysis). And when the 25 function  $f$  is bijective (in which case a different input always

provides a different output), if the number of rounds of the cipher is set at  $3m$ , then the probability of the cipher becomes  $P \leq p_i^{2m} \leq p_b^{4m}$ . In general, cipher are regarded as being secure against the differential and linear cryptanalysis schemes if  $P < 2^{-64}$ ; hence, it is  
5 necessary only to satisfy  $m > -16/\{\log_2(p_b)\}$ , and if  $p_b \leq 2^{-4}$ , it is possible to ensure security with a smaller number of rounds than 16 rounds needed in the DES. The probability of security changes for each multiple of  $m$  rounds.

10 The present invention ensures security against the differential and linear cryptanalysis with a relatively small number of rounds, and hence it permits implementation of a cryptographic device which copes with both security and low workload.

#### BRIEF DESCRIPTION OF THE DRAWINGS

15 Fig. 1 is diagram depicting the functional configuration of a conventional DES cryptographic device.

Fig. 2 is a diagram depicting a concrete functional configuration of an f-functional calculus part 12 in Fig. 1.

20 Fig. 3 is a diagram illustrating the functional configuration of Embodiment 1 of the present invention.

Fig. 4 is a diagram showing in detail an example of the functional configuration of a nonlinear function part 304 in Embodiment 1.

25 Fig. 5 is a diagram depicting a concrete example of a key-dependent linear transformation part 347 in Fig. 4.

Fig. 6 is a diagram illustrating the functional configuration of Embodiment 2 of the present invention.

Fig. 7A is a diagram showing in detail the functional configuration of a nonlinear function part 304 in Embodiment 2.

Fig. 7B is a diagram showing a concrete example of a linear transformation part 354 in the nonlinear function part 304.

5 Fig. 8 is a diagram illustrating the functional configuration of Embodiment 3 of the present invention.

Fig. 9 is a diagram showing in detail the functional configuration of a nonlinear function part 304 in Embodiment 3.

10 **BEST MODE FOR CARRYING OUT THE INVENTION**

**EMBODIMENT 1**

An embodiment of the present invention will be described below with reference to the accompanying drawings.

15 Fig. 3 depicts the functional configuration for an encryption procedure in the cryptographic device according to an embodiment of the present invention. The cryptographic device of the present invention also splits input data to two pieces of block data  $L_0$  and  $R_0$  and subjects them to round processing by  $n$  cascade-connected round processing parts  $38_0$  to  $38_{n-1}$  in a sequential order; each 20 round processing part  $38_i$  ( $i=0, 1, \dots, n-1$ ) is made up of a nonlinear function part 304 corresponding to the round function part 12 in Fig. 1, a linear operation part 305 corresponding to the XOR circuit 13 in Fig. 1 and a swapping part 306.

25 Input data  $P$ , which corresponds to a plaintext, is entered into the cryptographic device via an input part 301. The following key data is generated in advance by a extended key generation part 321 on the basis of the data input thereto from a key input part 320 and

stored in a key storage part 322.

{fk; k<sub>00</sub>, k<sub>10</sub>, k<sub>20</sub>; k<sub>01</sub>, k<sub>11</sub>, k<sub>21</sub>; ..., k<sub>0(n-1)</sub>, k<sub>1(n-1)</sub>, k<sub>0(n-1)</sub>; ek}

The input plaintext data P is transformed in a key-dependent initial linear transformation part 302 with the extend key fk stored in the

5 key storage part 322, thereafter being split in an initial splitting part 303 to two pieces of block data L<sub>0</sub> and R<sub>0</sub>. For example, 64-bit data is split to two pieces of 32-bit block data L<sub>0</sub> and R<sub>0</sub>. The block data R<sub>0</sub> is input to the nonlinear function part 304 of the 0-th round processing part 38<sub>0</sub>, together with the extended key k<sub>00</sub>, k<sub>10</sub> and k<sub>20</sub> stored in the key storage part 322, and in the nonlinear function part it is transformed to data Y<sub>0</sub>. The data Y<sub>0</sub> and the block data L<sub>0</sub> are transformed to data L<sub>0</sub>\* through an operation in the linear operation part 305. The data L<sub>0</sub>\* and the block data R<sub>0</sub> are subjected to data-position swapping in the swapping part 306 to provide L<sub>1</sub> = R<sub>0</sub> and R<sub>1</sub> = L<sub>0</sub>\*; L<sub>1</sub> and R<sub>1</sub> are fed to the next first round processing part 38<sub>1</sub>.

Thereafter, in an i-th round processing part 38<sub>i</sub> (i=1, ..., n-1) the same processing as described above is repeated for two pieces of block data L<sub>i</sub> and R<sub>i</sub>. That is, in the i-th round processing part 38<sub>i</sub>

20 the data R<sub>i</sub>, one of the two pieces of block data L<sub>i</sub> and R<sub>i</sub>, is input into the nonlinear function part 304, together with the extended key k<sub>0i</sub>, k<sub>1i</sub> and k<sub>2i</sub> stored in the key storage part 322, and in the nonlinear function part 304 it is transformed to data Y<sub>i</sub>. The data Y<sub>i</sub> and the block data L<sub>i</sub> are transformed to data L<sub>i</sub>\* by an operation in 25 the linear operation part 305. The data L<sub>i</sub>\* and the data R<sub>i</sub> are swapped in data position in the swapping part 306 to L<sub>i+1</sub> = R<sub>i</sub> and R<sub>i+1</sub> = L<sub>i</sub>\*. The linear operation part 305 is one that performs, for

instance, an exclusive-OR operation.

Letting  $n$  represent the repeat count suitable to ensure security of the cryptosystem, two pieces of data  $L_n$  and  $R_n$  are obtained as the result of such repeated processing by the round processing parts 38<sub>0</sub>

5 to 38<sub>n-1</sub>. These pieces of data  $L_n$  and  $R_n$  are combined into a single piece of block data in a final combining part 307; for example, two pieces of 32-bit data  $L_n$  and  $R_n$  are combined to 64-bit data. Then the thus combined data is transformed in a key-dependent final linear transformation part 308 using the extended key  $ek$  stored in

10 the key storage part 322, and output data  $C$  is provided as a ciphertext from an output part 309.

To decrypt, the encryption procedure needs only to be reversed, by which the plaintext  $P$  can be derived from the ciphertext  $C$ . This can be done, for example, by inputting ciphertext data in place of the input data in Fig. 3 and then inputting the extended key in a sequential order reverse to that in Fig. 3, that is,  $ek, k_{0(n-1)}, k_{1(n-1)}$ ,  
15  $k_{2(n-1)}, \dots, k_{01}, k_{11}, k_{21}, k_{00}, k_{10}, k_{21}, f_k$ .

Fig. 4 illustrates the functional configuration of the nonlinear function part 304 used in each round processing part 38<sub>i</sub>. The block

20 data  $R_i$  to the  $i$ -th round processing part 38<sub>i</sub> constitutes input data to the nonlinear function part 304, together with the extended key  $k_{0i}$ ,  $k_{1i}$  and  $k_{2i}$  stored in the key storage part 322. The block data  $R_i$  is linearly transformed to data  $R_i^*$  in a key-dependent linear

25 transformation part 341 using the extended key  $k_{0i}$ . The data  $R_i^*$  is splitting, for instance, to four pieces of 8-bit data  $in_0, in_1, in_2$  and  $in_3$  in a splitting part 342. The four pieces of data  $in_0, in_1, in_2$  and  $in_3$  are nonlinearly transformed to four pieces of data  $mid_{00}, mid_{01},$

mid<sub>02</sub> and mid<sub>03</sub> in nonlinear transformation parts 343, 344, 345 and 346, respectively, from which they are input to a key-dependent linear transformation part 347.

The key-dependent linear transformation part 347 is made up  
5 of four processing routes 30<sub>0</sub> to 30<sub>3</sub> each of which contains at least one exclusive OR circuit as depicted in Fig. 5; these processing routes are logically combined by those exclusive OR circuits. Each processing route performs a linear operation (an exclusive-OR operation) of its own data with those of the other processing routes  
10 to generate uniformed pieces of data in the respective processing routes; in the example of Fig. 5, they are further linearly processed by extended key k<sub>1i</sub>. That is, the pieces of data mid<sub>00</sub>, mid<sub>01</sub>, mid<sub>02</sub> and mid<sub>03</sub> are fed into the processing routes 30<sub>0</sub> to 30<sub>3</sub>, respectively. In the processing route 30<sub>1</sub> the pieces of input data mid<sub>00</sub> and mid<sub>01</sub>  
15 are exclusive ORed by an XOR 31<sub>1</sub>, and in the processing route 30<sub>2</sub> the pieces of input data mid<sub>02</sub> and mid<sub>03</sub> are exclusive ORed by an XOR 31<sub>2</sub>, and the outputs from the XOR 31<sub>1</sub> and the XOR 31<sub>2</sub> are exclusive ORed by an XOR 32<sub>2</sub>. The outputs from the XOR 31<sub>1</sub> and the XOR 32<sub>2</sub> are exclusive ORed by an XOR 33<sub>1</sub>, then the output from  
20 the XOR 33<sub>1</sub> and the input data mid<sub>00</sub> are exclusive ORed by an XOR 34<sub>0</sub>, and the output from the XOR 32<sub>2</sub> and the input data mid<sub>03</sub> are exclusive ORed by an XOR 34<sub>3</sub>. Furthermore, the outputs from the XORs 34<sub>0</sub>, 33<sub>1</sub>, 32<sub>2</sub> and 34<sub>3</sub> and extended key k<sub>1i0</sub>, k<sub>1i1</sub>, k<sub>1i2</sub> and k<sub>1i3</sub>  
25 are exclusive ORed by XORs 35<sub>0</sub> to 35<sub>3</sub>, from which mid<sub>10</sub>, mid<sub>11</sub>, mid<sub>01</sub> and mid<sub>13</sub> are output, respectively. That is, the input data mid<sub>00</sub>, mid<sub>01</sub>, mid<sub>02</sub> and mid<sub>03</sub> to the processing routes 30<sub>0</sub> to 30<sub>3</sub> are associated with one another and then undergo linear

transformations which are dependent on the key data  $k_{1i0}$ ,  $k_{1i1}$ ,  $k_{1i2}$  and  $k_{1i3}$ , respectively. In short, logical operations given by the following logical expressions are performed.

$$\begin{aligned} \text{mid}_{10} &= \text{mid}_{00} \oplus \text{mid}_{02} \oplus \text{mid}_{03} \oplus k_{1i0} \\ 5 \quad \text{mid}_{11} &= \text{mid}_{02} \oplus \text{mid}_{03} \oplus k_{1i1} \\ \text{mid}_{12} &= \text{mid}_{00} \oplus \text{mid}_{01} \oplus \text{mid}_{02} \oplus \text{mid}_{03} \oplus k_{1i2} \\ \text{mid}_{13} &= \text{mid}_{00} \oplus \text{mid}_{01} \oplus \text{mid}_{02} \oplus k_{1i3} \end{aligned} \quad (11)$$

As is evident from these expressions, the output from each processing route of the key-dependent linear transformation part 34 10 contains input data of at least two or more other routes in the form of exclusive ORs in this example, and accordingly the output data of each route is so uniformed as to contain two or more components of the four pieces of input data.

These pieces of output data  $\text{mid}_{10}$ ,  $\text{mid}_{11}$ ,  $\text{mid}_{12}$  and  $\text{mid}_{13}$  are 15 nonlinearly transformed to corresponding pieces of data  $\text{out}_0$ ,  $\text{out}_1$ ,  $\text{out}_2$  and  $\text{out}_3$  in nonlinear transformation parts 348, 349, 350 and 351, respectively, and the pieces of data are provided as output data from the respective processing routes to a combining part 352, wherein they are combined into a single piece of block data  $Y_i^*$ .

That is, for example, four pieces of 8-bit data are combined into one 20 piece of 32-bit data. The data  $Y_i^*$  is linearly transformed by extended key  $k_{2i}$  to data  $Y_i$  in a key-dependent linear transformation part 353; thus, the output data  $Y_i$  from the nonlinear function part 304 is generated. The nonlinear transformation parts 25 343 to 346 and 348 to 351 are similar, for instance, to the S-box in the DES, and they are each formed, for example, by a ROM whose output data differs with the input data thereto.

The four nonlinear transformation parts 343 to 346 are arranged in parallel and their transformation processes are not associated with one another, and hence they can be executed in parallel; accordingly, an increase in the processing time by 5 increasing the number of such nonlinear transformation parts can be dealt with by the parallel processing thereof. The same is true of the nonlinear transformation parts 348 to 351.

The time necessary for processing in the linear operation part 305 (Fig. 3) and the key-dependent linear transformation parts 341, 10 347 and 353 (Fig. 4), which constitute each round processing part 38<sub>i</sub>, is appreciably shorter than the time required to perform processing of the nonlinear transformation parts 343 to 345 and 348 to 351 similar to the S-box; therefore, the time necessary for encryption processing is substantially in proportion to the number of 15 S-boxes or nonlinear transformation parts used. However, since the key-dependent linear transformation part 347 renders plural pieces of input data into uniformed outputs as described previously, it is possible to omit one or more of the nonlinear transformation parts 348 to 351 and input the corresponding pieces of data into the 20 combining part 352 when it is preknown that the key-dependent linear transformation part 347 performs such a particular linear transformation as described above with reference to Fig. 5. This can be done without diminishing the security against the differential and linear cryptanalysis, and the workload for encryption can be 25 reduced by the number of nonlinear transformation parts thus omitted. For example, when the key-dependent linear transformation part 347 is such as shown in Fig. 5, even if the

- nonlinear transformation parts 349 and 350 are omitted and the pieces of data  $mid_{11}$  and  $mid_{12}$  are fed intact into the combining part 352, the security against the differential and linear cryptanalysis remains unchanged but the encryption speed increases about 33%.
- 5 In other words, when the operation of the key-dependent linear transformation part 347 is predetermined, the presence of one or more of the nonlinear transformation parts 348 to 351 may sometimes has nothing to do with the security against the differential and linear cryptanalysis, in which case they can be omitted.
- 10

Incidentally, in Fig. 3 the generation of the extended key  $\{fk, k_{00}, k_{10}, k_{20}, k_{01}, k_{11}, \dots, k_{0(n-1)}, k_{1(n-1)}, k_{2(n-1)}, ek\}$  by the extended key generation part 321 can be done in the same manner as in the extended key generating part 16 for the DES in Fig. 1.

- 15 If the above cryptographic device is designed so that, for example, the nonlinear transformation parts 343 to 346 and 348 to 351 are each approximated with a probability of  $p_b = 2^{-6}$  by the differential and linear cryptanalysis techniques and that each round processing part 38<sub>i</sub> performs the nonlinear transformation twice, 20 that is, performs in tandem the processing by the transformation parts 343 to 346 and the processing by the transformation parts 348 to 351, each round is approximated with a probability of  $p_i \leq 2^{-12}$ ; setting the number n of rounds at  $n = 3m$ , the round processing of the entire cryptographic device is approximated with a probability of  $P \leq 2^{-24m}$ . For example, if  $m = 4$  (the number of rounds: 12), the probability becomes  $P \leq 2^{-96}$ , which satisfies a security condition  $P < 2^{-64}$  with a smaller number of rounds than that 16 of the DES,
- 25

providing a cryptographic device with a sufficiently high level of security against the differential and linear cryptanalysis. That is, according to the present invention, the security against cryptanalysis can be increased by configuring the round function 12 (Fig. 1) to 5 perform the nonlinear transformation twice in succession.

Since the key-dependent initial linear transformation part 302, the key-dependent final linear transformation part 308 and the key-dependent linear transformation parts 347 and 353 are linear transformation parts that are dependent on extended keys, they 10 provide sufficient security against other cryptanalysis as well as the differential and linear cryptanalysis, ensuring the implementation of a cryptographic device that attaches prime importance on security.

The present invention is not limited specifically to this embodiment; for example, if it is desirable to speed up encryption, it 15 is possible to omit any one or all of these key-dependent initial linear transformation part 302, the key-dependent final linear transformation part 308 and the key-dependent linear transformation part 353 as in the embodiment described later on. In this instance, the security against the differential and linear 20 cryptanalysis will not be diminished on the one hand, but on the other hand the processing speed for encryption can be increased corresponding to the number of operations omitted. But there is a fear of providing decreased security against the other cryptanalysis. Alternatively, any one or all of the key-dependent initial linear 25 transformation part 302, the key-dependent final transformation part 308 and the key-dependent linear transformation parts 347 and 353 may be modified to key-independent linear transformation

parts. This will not diminish the security against the other cryptanalysis as well as the differential and linear cryptanalysis, and makes it possible to increase the processing speed for encryption by implement optimization. The linear transformation parts each 5 perform a transposition of swapping bit positions of input data in a predetermined relationship, a rotation of the input data by a predetermined number of bits, and so forth. The key-dependent linear transformation parts each perform a rotation by the number of bits corresponding to the extended key, an exclusive OR of the 10 input data and the extended key, and so on.

EMBODIMENT 2

Fig. 6 illustrates an embodiment which omits middle two of the second four nonlinear transformation parts 348 to 351 in the 15 nonlinear function part 304 (Fig. 4) of the first embodiment shown in Fig. 3. In this embodiment there are also omitted the key-dependent initial linear transformation part 302 and the key-dependent final linear transformation part 308.

The input data P equivalent to a plaintext is input into the 20 cryptographic device via the input part 301. The input data P is split to two pieces of block data  $L_0$  and  $R_0$  in the initial splitting part 303. The block data  $R_0$  is input to the nonlinear function part 304 of the 0-th round processing part  $38_0$ , together with the extended key  $k_{00}$  and  $k_{20}$  stored in the key storage part 322, wherein it is 25 transformed to data  $Y_0$  through transformation processing. The data  $Y_0$  and the data  $L_0$  are transformed to data  $L_0^*$  by an operation in the linear operation part 305. The data  $L_0^*$  and the data  $R_0$  are

subjected to data-position swapping in the swapping part 306 to provide  $L_1 = R_0$  and  $R_1 = L_0^*$ . Thereafter, in the i-th round processing part 38<sub>i</sub> ( $i=1, \dots, n-1$ ) the same processing as described above is repeated for the two pieces of data  $L_i$  and  $R_i$ . That is, the  
5 data  $R_i$ , one of the two pieces of data  $L_i$  and  $R_i$ , is input into the nonlinear function part 304, together with the extended key  $k_{0i}$  and  $k_{2i}$  stored in the key storage part 322, and in the nonlinear function part 304 it is transformed to data  $Y_i$ . The data  $Y_i$  and the data  $L_i$  are transformed to data  $L_i^*$  by an operation in the linear operation part  
10 305. The data  $L_i^*$  and the data  $R_i$  are swapped in data position in the swapping part 306 for transformation to  $L_{i+1} = R_i$  and  $R_{i+1} = L_i^*$ .

Letting  $n$  represent the repeat count suitable to ensure security of the cryptosystem, two pieces of data  $L_n$  and  $R_n$  are obtained by such  $n$  repeated rounds of processing. These pieces of data  $L_n$  and  $R_n$  are combined in the final combining part 307, and the combined output is provided to the output part 309, from which the output data  $C$  is output as the ciphertext.  
15

To decrypt, the encryption procedure needs only to be reversed, by which the plaintext  $P$  can be derived from the ciphertext  $C$ .

20 Fig. 7A illustrates the functional configuration of the nonlinear function part 304 of the i-th round processing part 38<sub>i</sub> in the Fig. 6. The data  $R_i$  from the preceding round processing part constitutes input data to the nonlinear function part 304, together with the extended key  $k_{0i}$  and  $k_{2i}$  stored in the key storage part 322. The data  $R_i$  is linearly transformed to data  $R_i^*$  in the key-dependent linear transformation part 341 using the extended key  $k_{0i}$ . Then the data  $R_i^*$  is split to four pieces of data  $in_0, in_1, in_2$  and  $in_3$  in the  
25

splitting part 342. The four pieces of data  $in_0$ ,  $in_1$ ,  $in_2$  and  $in_3$  are nonlinearly transformed to four pieces of data  $mid_{00}$ ,  $mid_{01}$ ,  $mid_{02}$  and  $mid_{03}$  in the nonlinear transformation parts 343, 344, 345 and 346, respectively, from which they are input to a linear  
5 transformation part 354. In the linear transformation part 354 the four pieces of input data are transformed so that they are mutually associated between the four processing routes  $30_0$  to  $30_3$  as depicted in Fig. 7B. This is the same example as in the case of omitting the logical operation with the extended key in Fig. 5 and can be given by  
10 the following expressions.

$$\begin{aligned} mid_{10} &= mid_{00} \oplus mid_{02} \oplus mid_{03} \\ mid_{11} &= mid_{02} \oplus mid_{03} \\ mid_{12} &= mid_{00} \oplus mid_{01} \oplus mid_{02} \oplus mid_{03} \\ mid_{13} &= mid_{00} \oplus mid_{01} \oplus mid_{02} \end{aligned} \tag{12}$$

15 By this linear transformation, uniformed data  $mid_{10}$ ,  $mid_{11}$ ,  $mid_{12}$  and  $mid_{13}$  are generated, and two pieces of data  $mid_{10}$  and  $mid_{13}$  are nonlinearly transformed to data  $out_0$  and  $out_3$  in the nonlinear transformation parts 348 and 351, respectively, after which the four pieces of data  $out_0$ ,  $mid_{11}$ ,  $mid_{12}$  and  $out_3$  are  
20 combined into a single piece of data  $Y_i^*$  in the combining part 352. Finally, the data  $Y_i^*$  is linearly transformed to the data  $Y_i$  in the key-dependent linear transformation part 353 using the extended key  $k_{2i}$ , by which the output data  $Y_i$  from the nonlinear function part 304 is generated.

25 The nonlinear transformation parts 343 to 346 are arranged in parallel and their transformation processes are not associated with one another, and hence they can be executed in parallel. The same

goes for the nonlinear transformation parts 348 and 351. In this embodiment, since the number of second nonlinear transformations in each nonlinear function part 304 is reduced to the outer two (348 and 351) alone, the workload for encryption or decryption can be decreased accordingly.

Incidentally, the extended key  $k_i$  is data transformed in the extended key generation part 321 from the secret key Key input into the cryptographic device via the key input part 320 and stored in the key storage part 322.

In the case of the above cryptographic device, for example, if the nonlinear transformation parts 343 to 346, 348 and 351 are designed to provide an approximate representation with the probability of  $p_b = 2^{-6}$  against the differential and linear cryptanalysis, each round processing part can provide an approximate representation with the same probability of  $p_i \leq 2^{-12}$  as in Embodiment 1; setting the number n of rounds at  $n = 3m$ , the cryptographic device provides an approximate representation with the probability of  $P \leq 2^{-24m}$  as a whole. For example, if  $m = 4$  (the number of rounds: 12), the probability becomes  $P \leq 2^{-96}$ , ensuring a sufficiently high level of security against the differential and linear cryptanalysis.

Moreover, the presence of the key-dependent linear transformation part 353 provides a margin of security against other cryptanalysis than the differential and linear cryptanalysis, and the simplified configuration as compared with that of Embodiment 1 reduces the workload. That is, the cryptographic device of this embodiment places importance on the balance between security and

reduced workload.

EMBODIMENT 3

Fig. 8 illustrates an embodiment which omits the key-dependent linear transformation part 353 in the nonlinear function part 304 of the second embodiment depicted in Fig. 6. The input data P equivalent to a plaintext is input into the cryptographic device via the input part 301. The input data P is split to two pieces of block data  $L_0$  and  $R_0$  in the initial splitting part 303. The block data  $R_0$  is input to the nonlinear function part 304 of the 0-th round processing part 38<sub>0</sub>, together with extended key  $k_0$  stored in the key storage part 322, wherein it is transformed to data  $Y_0$  through transformation processing. The data  $Y_0$  and the data  $L_0$  are transformed to data  $L_0^*$  by an operation in the linear operation part 305. The data  $L_0^*$  and the data  $R_0$  are subjected to data-position swapping in the swapping part 306 for transformation to  $L_1 = R_0$  and  $R_1 = L_0^*$ . Thereafter, in the i-th round processing part 38<sub>i</sub> the same processing as described above is repeated for the two pieces of data  $L_i$  and  $R_i$ . That is, the data  $R_i$ , one of the two pieces of data  $L_i$  and  $R_i$ , is input into the nonlinear function part 304, together with extended key  $k_i$  stored in the key storage part 322, and in the nonlinear function part 304 it is transformed to data  $Y_i$ . The data  $Y_i$  and the data  $L_i$  are transformed to data  $L_i^*$  by an operation in the linear operation part 305. The data  $L_i^*$  and the data  $R_i$  are swapped in data position in the swapping part 306 for transformation to  $L_{i+1} = R_i$  and  $R_{i+1} = L_i^*$ , and two pieces of block data  $L_{i+1}$  and  $R_{i+1}$  are output.

Letting  $n$  represent the repeat count suitable to ensure security of the cryptosystem, two pieces of data  $L_n$  and  $R_n$  are obtained by such  $n$  repeated rounds of processing. These pieces of data  $L_n$  and  $R_n$  are combined in the final combining part 307, and the combined output is provided to the output part 309, from which the output data  $C$  is output as the ciphertext.

The ciphertext  $C$  can be deciphered to the plaintext  $P$  by following the encryption procedure in reverse.

Fig. 9 illustrates the functional configuration of the nonlinear function part 304 in the Fig. 8. The data  $R_i$  to the nonlinear function part 304 is fed to the key-dependent linear transformation part 341, together with the extended key  $k_i$  stored in the key storage part 322. The data  $R_i$  is linearly transformed to data  $R_i^*$  in the key-dependent linear transformation part 341 using the extended key  $k_i$ . Then the data  $R_i^*$  is split to four pieces of data  $in_0$ ,  $in_1$ ,  $in_2$  and  $in_3$  in the splitting part 342. The four pieces of data  $in_0$ ,  $in_1$ ,  $in_2$  and  $in_3$  are nonlinearly transformed to four pieces of data  $mid_{00}$ ,  $mid_{01}$ ,  $mid_{02}$  and  $mid_{03}$  in the nonlinear transformation parts 343, 344, 345 and 346, respectively, from which they are input to the linear transformation part 354. The linear transformation part 354 linearly transforms them to the following pieces of data  $mid_{10}$ ,  $mid_{11}$ ,  $mid_{12}$  and  $mid_{13}$ , for example, in the same manner as described above with reference to Fig. 7B in Embodiment 2.

$$\begin{aligned} mid_{10} &= mid_{00} \oplus mid_{02} \oplus mid_{03} \\ 25 \quad mid_{11} &= mid_{02} \oplus mid_{03} \\ mid_{12} &= mid_{00} \oplus mid_{01} \oplus mid_{02} \oplus mid_{03} \\ mid_{13} &= mid_{00} \oplus mid_{01} \oplus mid_{02} \end{aligned} \tag{13}$$

Then the two pieces of data mid<sub>10</sub> and mid<sub>13</sub> are nonlinearly transformed to data out<sub>0</sub> and out<sub>3</sub> in the nonlinear transformation parts 348 and 351, respectively, after which the four pieces of data out<sub>0</sub>, mid<sub>11</sub>, mid<sub>12</sub> and out<sub>3</sub> are combined into a single piece of data in the combining part 352, by which the output data Y<sub>i</sub> from the nonlinear function part 304 is generated.

The nonlinear transformation parts 343 to 346 are arranged in parallel and their transformation processes are not associated with one another, and hence they can be executed in parallel. The same goes for the nonlinear transformation parts 348 and 351.

Incidentally, the extended key k<sub>i</sub> is data transformed in the extended key generation part 321 from the secret key Key input into the cryptographic device via the key input part 320 and stored in the key storage part 322.

In the case of the above cryptographic device, for example, if the nonlinear transformation parts 343 to 346, 348 and 351 are designed to provide an approximate representation with the probability of  $p_b = 2^{-6}$  against the differential and linear cryptanalysis, each round processing part can provide an approximate representation with the probability of  $p_i \leq 2^{-12}$ ; setting the number n of rounds at n = 3m, the cryptographic device provides an approximate representation with the probability of  $P \leq 2^{-24m}$  as a whole. For example, if m = 4 (the number of rounds: 12), the probability becomes  $P \leq 2^{-96}$ , ensuring a sufficiently high level of security against the differential and linear cryptanalysis.

Moreover, since the cryptographic device of this embodiment has a configuration that includes the minimum number of parts

required to provide a sufficient level of security against the differential and linear cryptanalysis, the workload is reduced and the encryption or decryption speed is improved accordingly.

In the above, the splitting part 342 in the nonlinear function  
5 part 304 needs not always to split the input data into four but may also split it to an arbitrary number of pieces. In the case splitting the data into four, the number of second nonlinear transformation parts may be reduced to only two as depicted in Figs. 7A and 9.

In the following table there are shown, in comparison with the  
10 case of the DES of Figs. 1 and 2, the security level per round, the number of rounds satisfying the security requirement and the workload (the number of steps) necessary therefor in the case of using six nonlinear transformation parts (343 to 346, 348, 351) in the nonlinear function part 304 (a round function) depicted in the  
15 second and third embodiments described above. In the comparison, the embodiments of the present invention used a total of 32 bits for the data to the nonlinear transformation parts 343 to 346 which correspond to the S-boxes of the DES, and hence the data to each nonlinear transformation part was 8-bit; therefore, the size of each  
20 S-box was made 8-bit and consequently, the number of S-boxes was four.

Comparative Table

	No. of S-boxes per round	Security level per round	Required No. of rounds	No. of steps
DES	4	$2^{-6}$	17	68
This invention	6	$2^{-12}$	9	54

As will be seen from this table, the number of S-boxes (the number of nonlinear transformation parts) per round in the present invention is larger than in the DES, but the security level per round in the present invention is twice that of the DES. On this account, the number of rounds required to meet the security requirement is smaller than in the case of DES, and the workload (the number of steps) necessary for providing the security is also smaller.

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#### EFFECT OF THE INVENTION

As described above in detail, according to the present invention, the input data is split to plural pieces of data in the nonlinear function part, then these pieces of data are nonlinearly transformed and linearly transformed in association with each other, and at least one part of such linearly transformed data is nonlinearly transformed, by which it is possible to provide a highly secure cryptographic device for concealing data in data communication or storage.

WHAT IS CLAIMED IS

1. A cryptographic device which encrypts input data by sequentially processing it by a plurality of round processing which nonlinearly transforms it using extended key, comprising:
  - an initial splitting part which splits the input data to two pieces of block data;
  - a key storage part for storing extended key;
  - a plurality of cascade-connected round processing parts which are supplied with said two pieces of block data and sequentially process them using said extended key; and
  - a final combining part which combines two pieces of block data output from the last round of said plurality of cascade-connected round processing parts into a single piece of data and outputs it;
    - wherein each of said plurality of round processing part comprises:
      - a nonlinear function part which transforms one of two pieces of block data input thereto from the preceding stage, depending on extended key stored in said key storage part;
      - a linear operation part which linearly operates the output data from said nonlinear function part and the other of said two pieces of block data; and
      - a swapping part which swaps the output data from said linear operation part and the input block data to said nonlinear function part and provides the two pieces of swapped data as two pieces of input block data to said round processing part of the next round; and
      - wherein said nonlinear function part comprises:

a key-dependent linear transformation part which linearly transforms input data based on extended key stored in said key storage part to thereby generate transformed data;

a splitting part which splits the transformed data from said key-dependent linear transformation part to a plurality of bit strings;

a plurality of first nonlinear transformation parts which nonlinearly transform these bit strings, respectively, and output transformed data;

a first linear transformation part which linearly transforms the transformed data from said plurality of first nonlinear transformation parts in association with each other and outputs a plurality of pieces of uniformed data to a plurality of routes, respectively;

a second nonlinear transformation part provided in at least one of said plurality of routes, for nonlinearly transforming said uniformed data from the corresponding one of said first linear transformation parts, and for outputting the transformed data as data of that route; and

a final combining part which combines data from said plurality of routes into output data of said nonlinear function part.

2. The cryptographic device of claim 1, wherein said first linear transformation part comprises a key-dependent linear operation part which linearly transforms said plurality of pieces of uniformed data based on extended key stored in said key storage part and outputs the plurality of transformed data as data of said plurality of routes.

3. The cryptographic device of claim 1 or 2, wherein there is provided a second linear transformation part which linearly transforms the output data from said combining part to provide the output data of said nonlinear function part.

4. The cryptographic device of claim 3, wherein said second linear transformation part is a linear transformation part which performs a linear transformation based on extended key stored in said key storage part.

5. The cryptographic device of claim 4, wherein said first linear transformation part comprises at least one exclusive OR circuit provided in each of said plurality of routes, for outputting said uniformed data to said each route by an exclusive-OR operation of data of said each route and data of other routes.

6. The cryptographic device of any one of claims 1 through 5, wherein there is provided an initial linear transformation part which linearly transforms said input data and supplies it to said initial splitting part.

7. The cryptographic device of claim 6, wherein said initial linear transformation part is a transformation part which performs a linear transformation based on extended key stored in said key storage part.

8. The cryptographic device of any one of claims 1 through 7, wherein there is provided a final linear transformation part which linearly transforms the output data of said final combining part to provide it as the output of said cryptographic device.

9. The cryptographic device of claim 8, wherein said final linear transformation part is a transformation part which performs a linear

transformation based on extended key stored in said key storage part.

10. The cryptographic device of any one of claims 1 through 9, wherein said plurality of routes are first, second, third and fourth routes arranged in this order.

11. The cryptographic device of claim 10, wherein said second nonlinear transformation part is provided in each of said four routes.

12. The cryptographic device of claim 10, wherein said second nonlinear transformation part is provided in each of said first and fourth routes.

13. The cryptographic device of claim 12, wherein said first linear transformation part comprises:

a first exclusive OR circuit provided in said second route, for carrying out the exclusive-OR between data of said first route and data of said second route;

a second exclusive-OR circuit provided in said third route, for carrying out the exclusive OR between data of said fourth route and data of said third route;

a third exclusive-OR circuit provided in said third route, for carrying out the exclusive OR between the output of said second exclusive-OR circuit and the output of said first exclusive-OR circuit;

a fourth exclusive-OR circuit provided in said second route, for carrying out the exclusive OR between the output of said first exclusive-OR circuit and the output of said third exclusive-OR circuit;

a fifth exclusive-OR circuit provided in said first route, for carrying out the exclusive OR between the data of said first route and the output of said fourth exclusive-OR circuit; and

00000000000000000000000000000000

a sixth exclusive-OR circuit provided in said fourth route, for carrying out the exclusive OR between the data of said fourth route and the output of said third exclusive-OR circuit.

## ABSTRACT OF THE DISCLOSURE

In a secret-key cryptographic device, there are cascade-connected a plurality of round processing parts and the round processing part of each i-th round is supplied with input data  $L_i$  and  $R_i$ , nonlinearly transforms the input data  $R_i$  in a nonlinear function part on the basis of extended key, then provides the exclusive OR between the nonlinearly transformed output and the input data  $L_i$  as data  $R_{i+1}$  for input into the next round and outputs the input data  $R_i$  as data  $L_{i+1}$  for input into the next round. The nonlinear function part of each round comprises: a key-dependent linear transformation part which performs a key-dependent linear transformation of the input  $R_i$ ; a splitting part which splits the linearly transformed output to four pieces of data  $in_0$ ,  $in_1$ ,  $in_2$  and  $in_3$ ; first nonlinear transformation parts which nonlinearly transform the four split pieces of data and output nonlinearly transformed data  $mid_{00}$ ,  $mid_{01}$ ,  $mid_{02}$  and  $mid_{03}$ , respectively; a key-dependent linear transformation part which associates these transformed outputs with each other and, at the same time, linearly transforms them based on extended key to output data  $mid_{10}$ ,  $mid_{11}$ ,  $mid_{12}$  and  $mid_{13}$ ; second nonlinear transformation parts which nonlinearly transform these transformed outputs, respectively, and output data  $out_0$ ,  $out_1$ ,  $out_2$  and  $out_3$ ; and a combining part which combines these transformed outputs into output data Y.

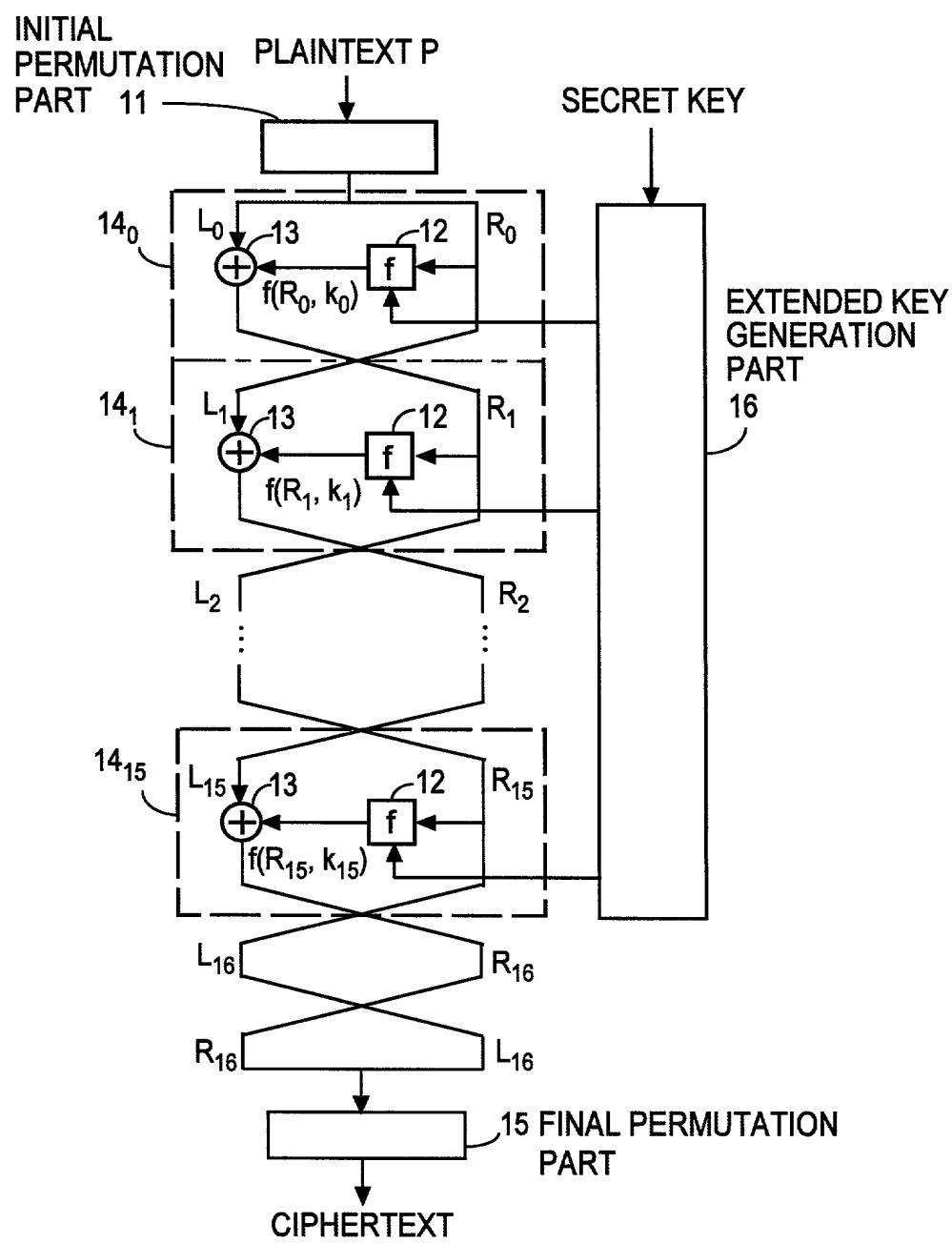


FIG. 1

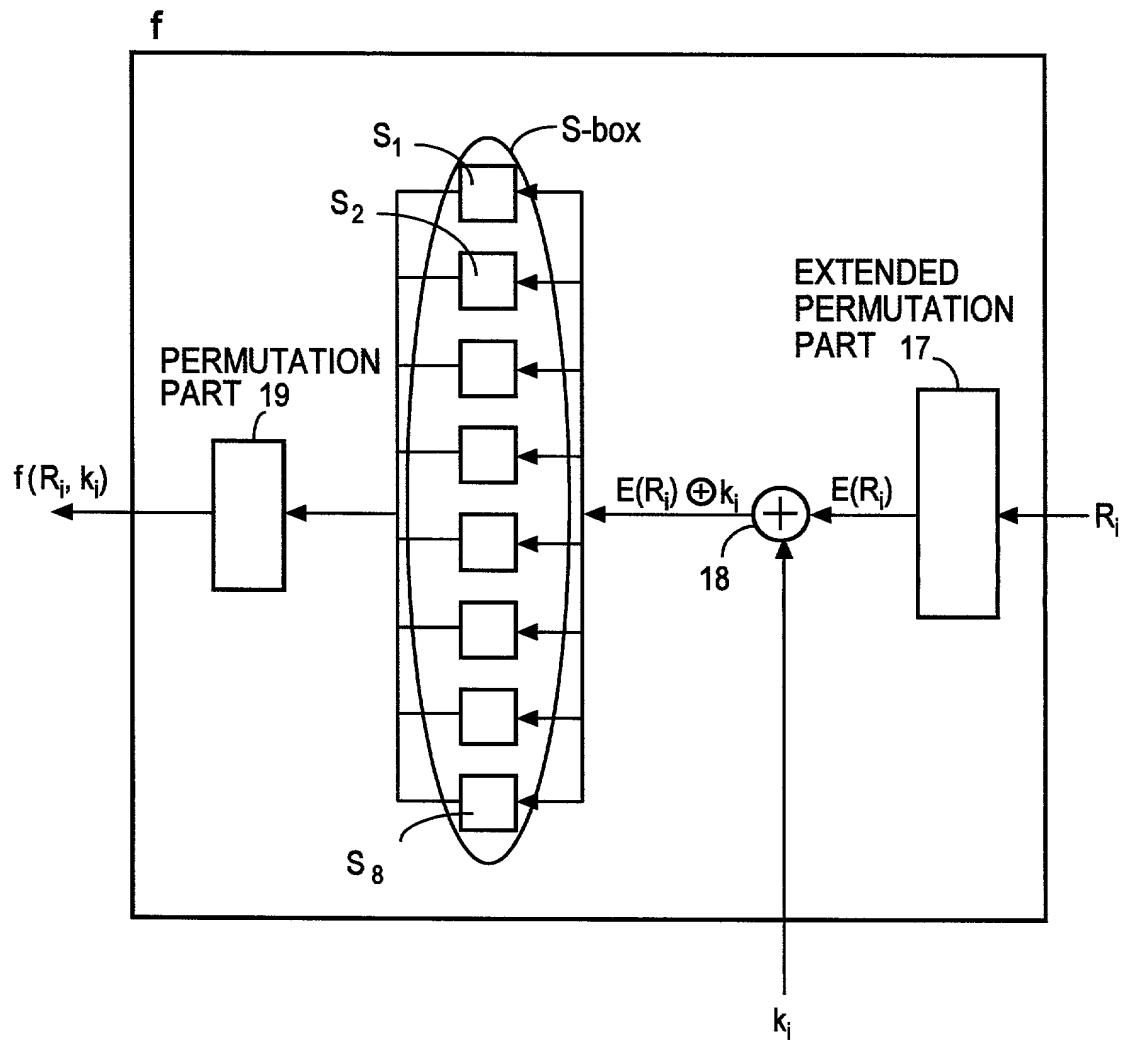


FIG. 2

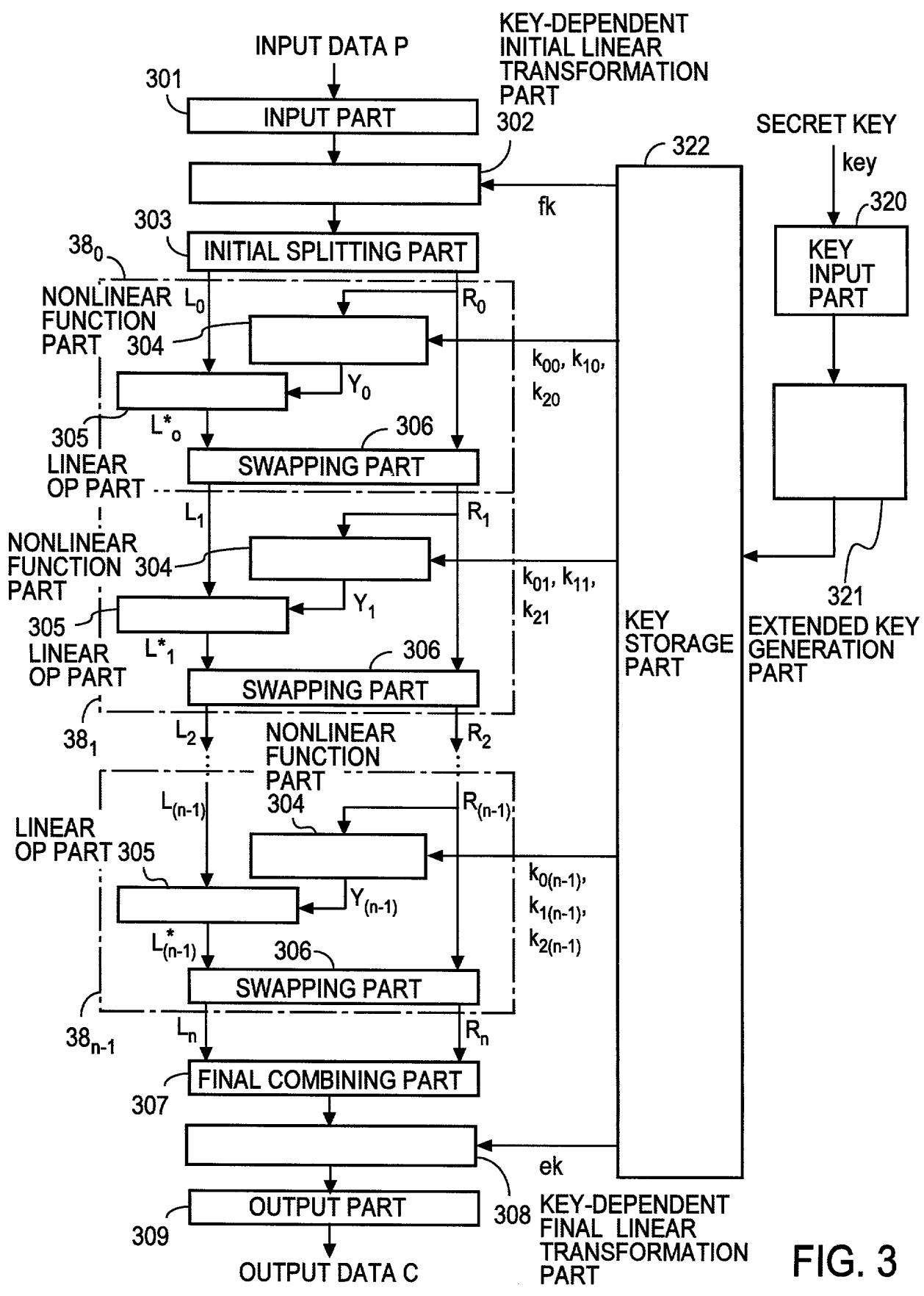


FIG. 3

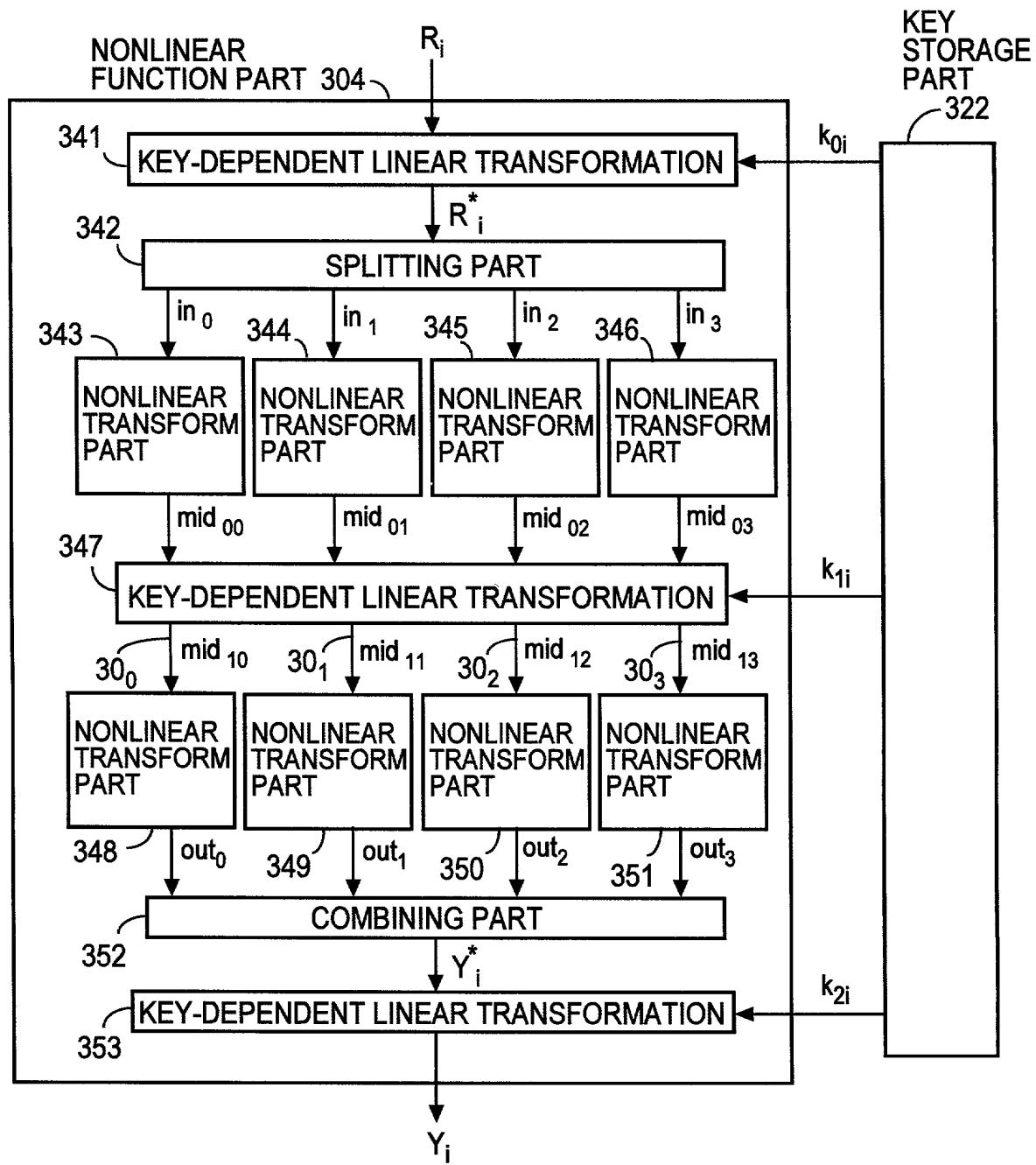


FIG. 4

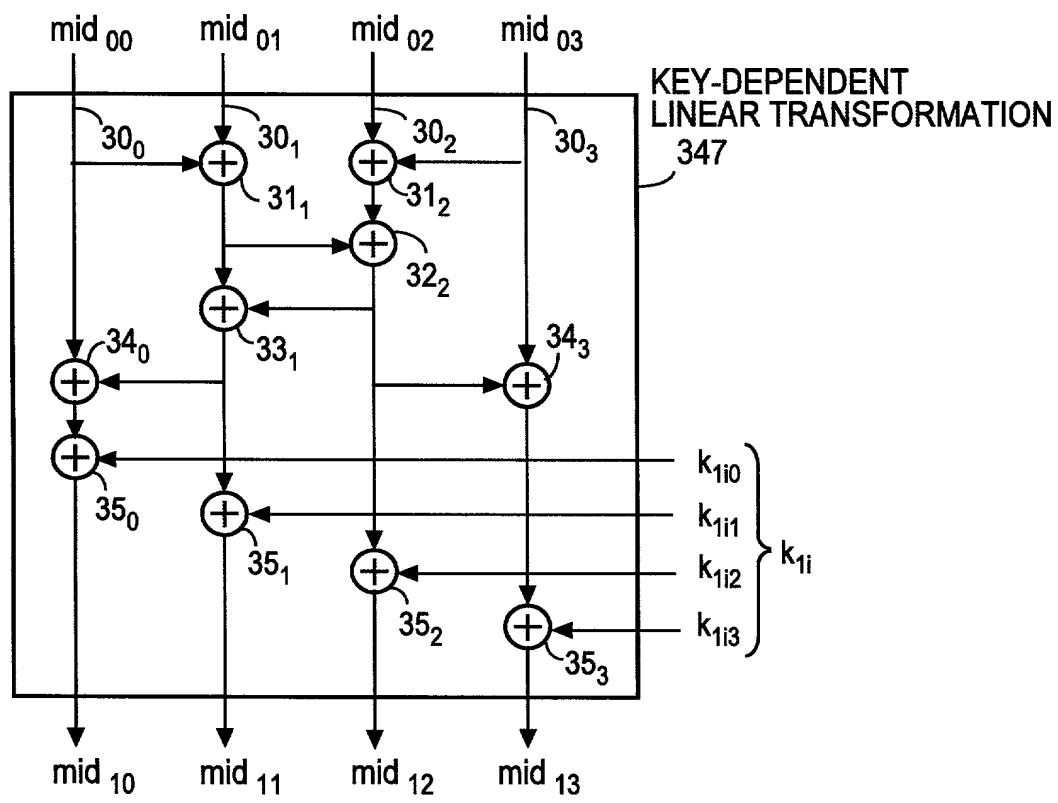


FIG. 5

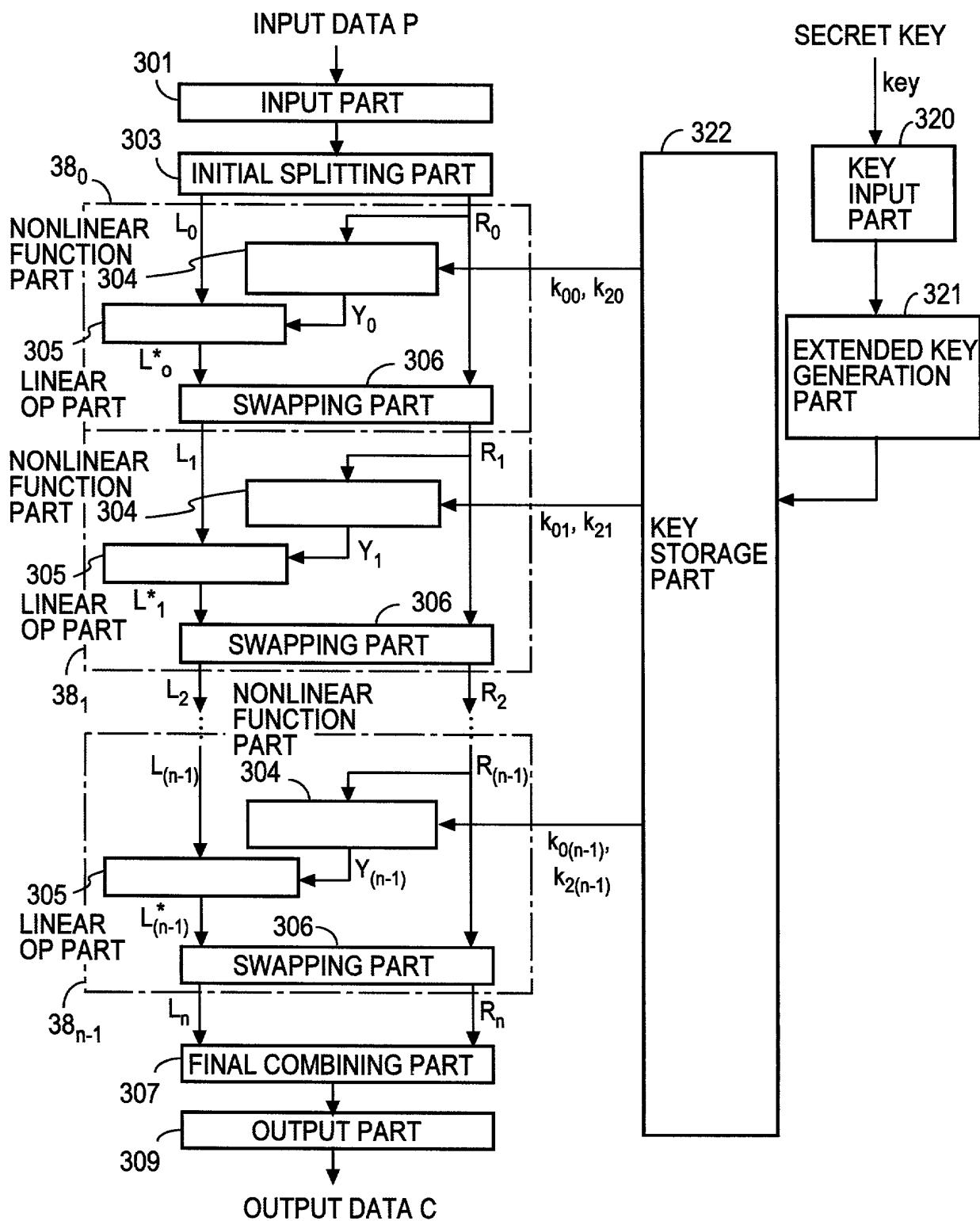


FIG. 6

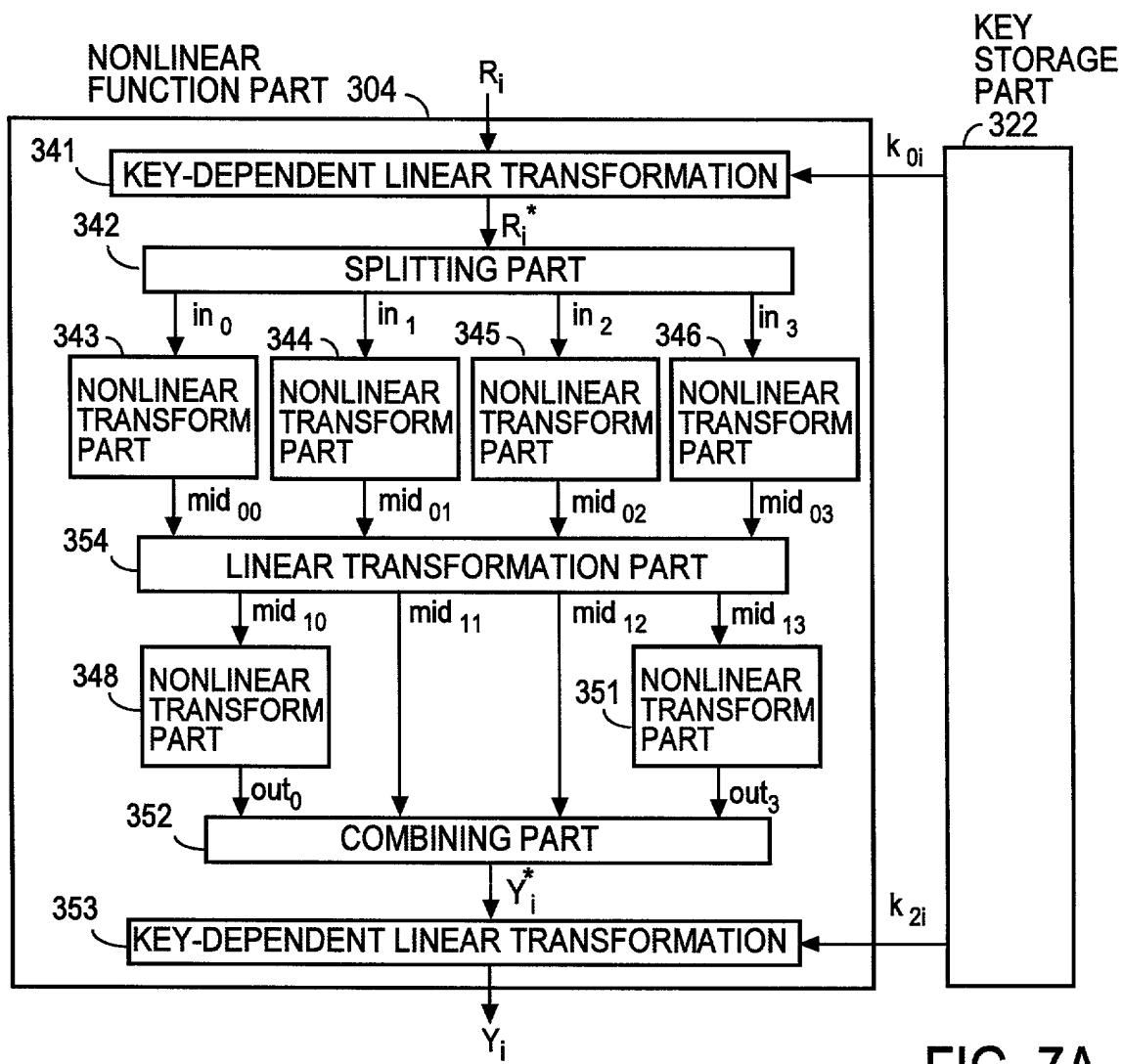


FIG. 7A

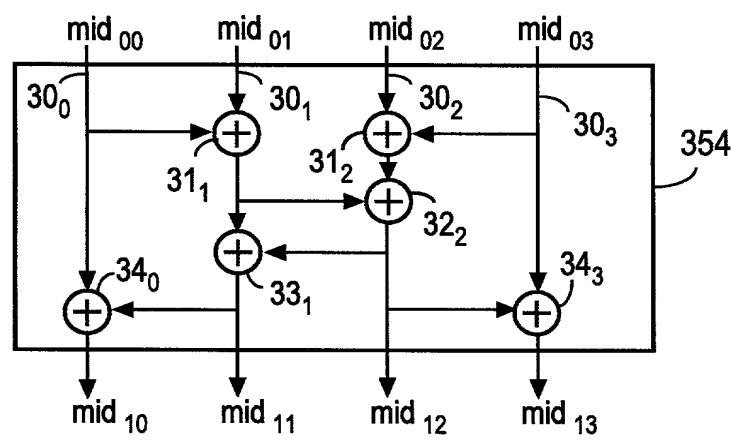


FIG. 7B

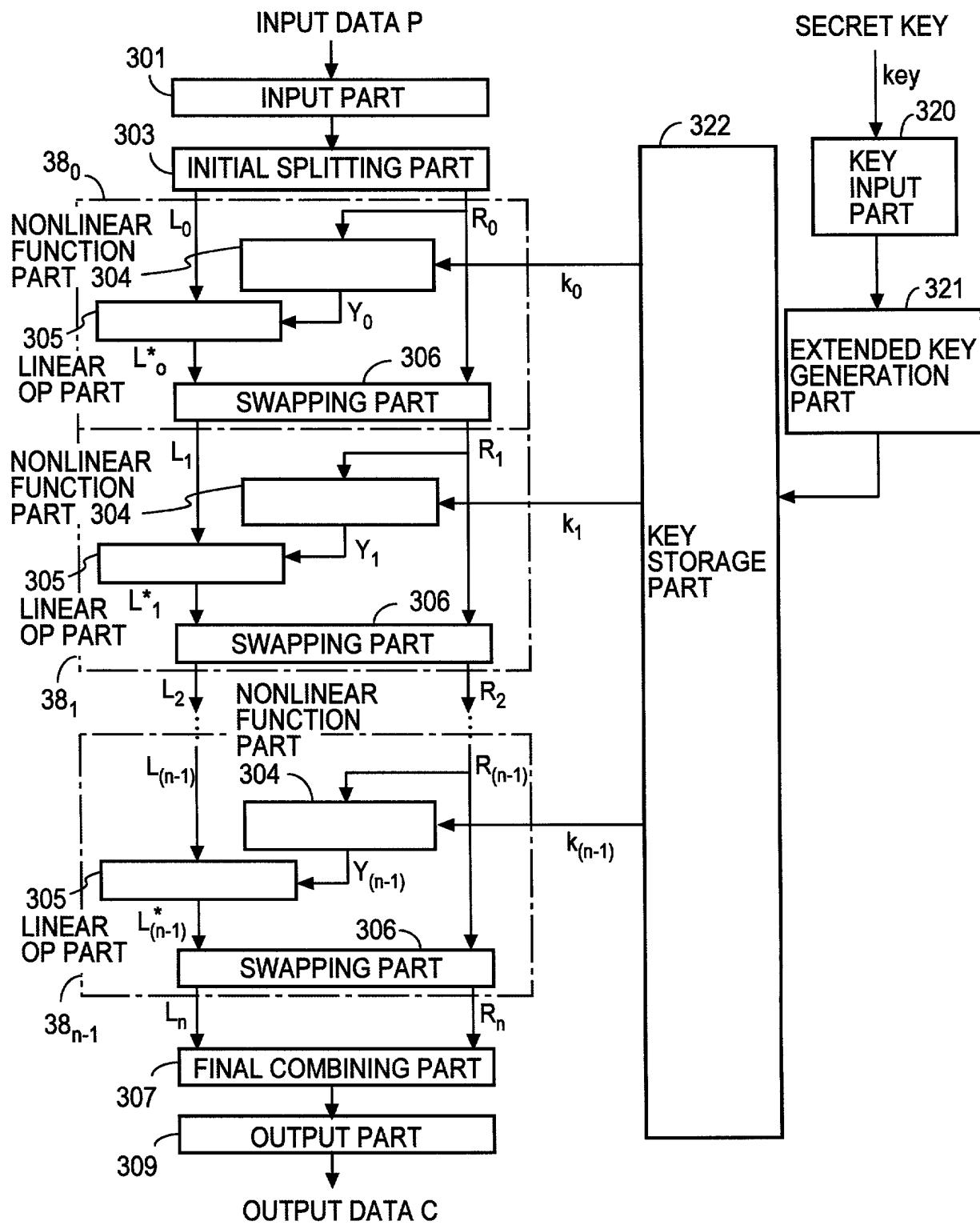


FIG. 8

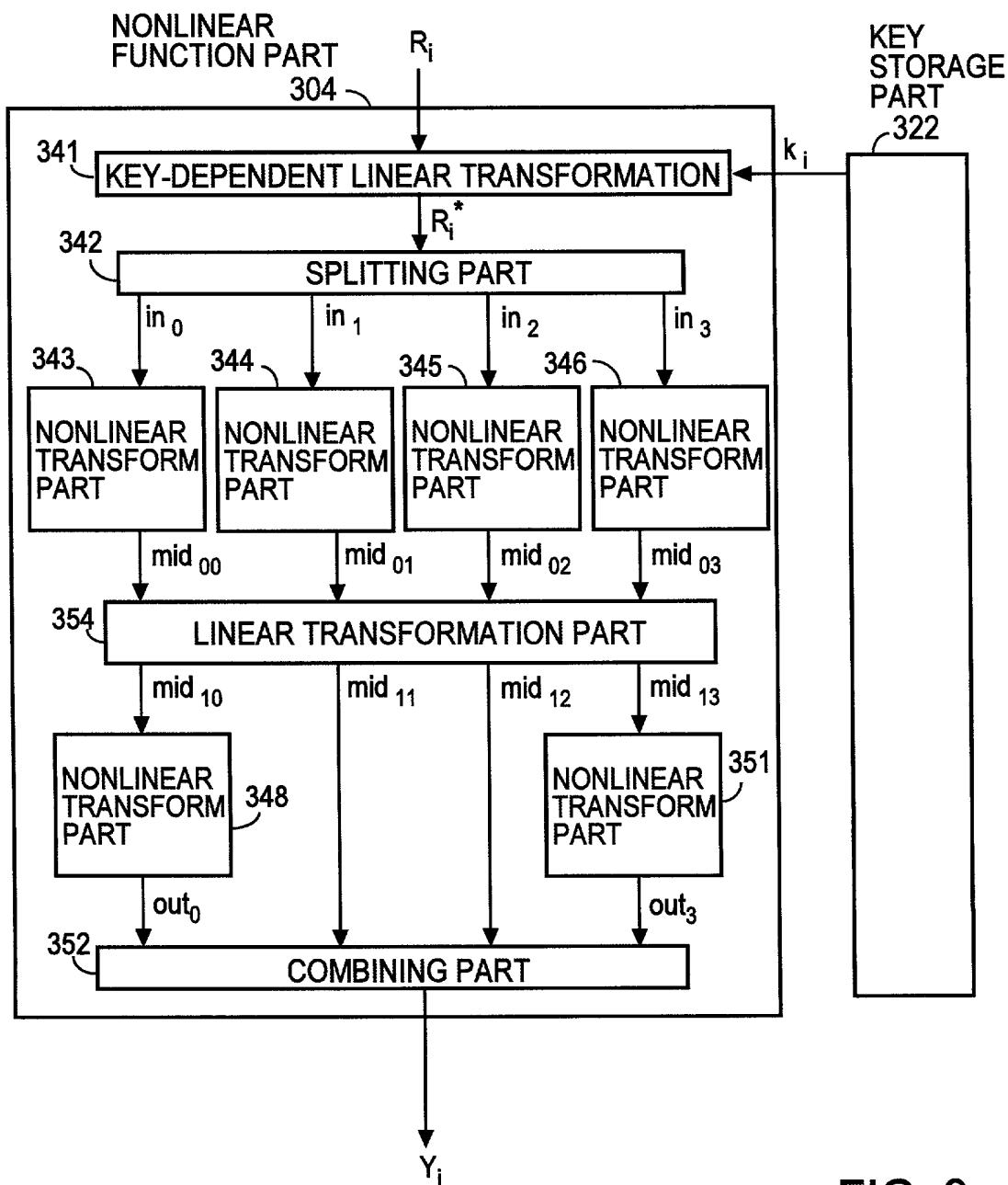


FIG. 9

## DECLARATION FOR PATENT APPLICATION

As a below-named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

### "CRYPTOGRAPHIC DEVICE"

the specification of which: (check one)

[XX] is attached hereto. [X] was filed on 30/06/1998, as United States Patent Application Serial No. or PCT International Application Number PCT/JP98/02915, and was amended on 19 (if applicable).

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to the patentability of this application in accordance with 37 CFR § 1.56(a).

Prior Foreign Application(s): I hereby claim foreign priority benefits under 35 U.S.C. § 119(a)-(d) or §365(b) of any foreign application(s) for patent or inventor's certificate listed below, or § 365(a) of any PCT international application which designated at least one country other than the United States of America, listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

Application No.	Country	Priority Claimed (Day/Month/Year Filed)	Priority Claimed (Day/Month/Year Filed)
<u>173672/97</u>	<u>Japan</u>	<u>June 30, 1997</u>	K [ ] Yes No [ ] [ ]
(Application No.)	(Country)	(Day/Month/Year Filed)	Yes No [ ] [ ]
(Application No.)	(Country)	(Day/Month/Year Filed)	Yes No [ ] [ ]

I hereby claim the benefit under Title 35, United States Code § 119(e) of any United States provisional application(s) listed below:

Application No.	Filing Date
_____	_____

I hereby claim the benefit under 35 U.S.C. § 120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by 35 U.S.C. § 112, first paragraph, I acknowledge the duty to disclose material information as defined in 37 CFR § 1.56(a) which occurred between the filing date of the prior application and the national or PCT international filing date of this application:

(U.S. Application Serial No.)	(U.S. Filing Date)	(Status--patented, pending, abandoned)
(U.S. Application Serial No.)	(U.S. Filing Date)	(Status--patented, pending, abandoned)

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements are made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under 18 U.S.C. § 1001 and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

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